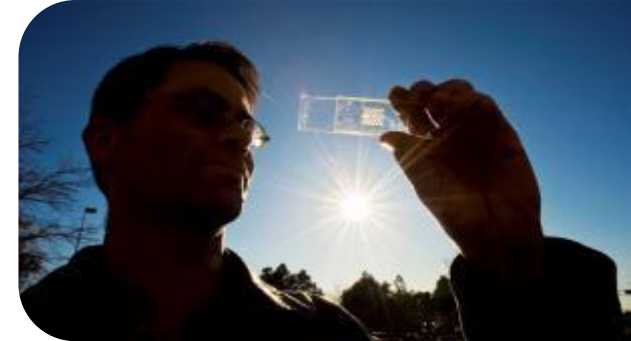


Exceptional service in the national interest



Micro and Nano Fabrication at Sandia and Selected Technology Examples

Gil Herrera

Director, Microsystems Science & Technology

February 26, 2013

SAND# 2013-1936-C



Sandia National Laboratories is a multi-program laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

Outline

- Welcome and Conference Issue Explanation
- Micro and Nano Fabrication (MESA and CINT)
- Selected Fab Research Examples
- End of Moore's Law and Lessons from the Past

MESA's Trusted Foundry: Supplying Hi-Rel Rad Hard Microelectronics while supporting the Research Community



MESA Silicon Fab

- Radiation Hardened CMOS Process
 - 350nm, 3.3V, Radiation Hardened, Silicon on Insulator Digital and Mixed Signal Technology
 - 5-Level MEMS Technology
- Custom Technologies
 - Ion Traps
 - Chem/Bio Detection Technologies
 - Si Photonics
 - GaN Resonators
 - 3-D Integration
- Part of the US Govt Trusted Supplier Network DoD Category 1A Trusted Supplier Certification

MESA Micro Fab

- III-V Compound Semiconductor Fabrication
- Compound Semiconductor Epitaxial Growth
- Compound Semiconductor Discretes, IC's and Optoelectronics



125 Light Laboratories Support and Extract Value from the MESA Fabs





CINT is a Nanoscale Science Research Center (DOE/SC National User Facility)

“A DOE/SC user facility has **unique world-class research capabilities and technologies** which are **available broadly to science community** worldwide from universities, industry, private laboratories, and other Federal laboratories for work that will be **published in the open literature.**”

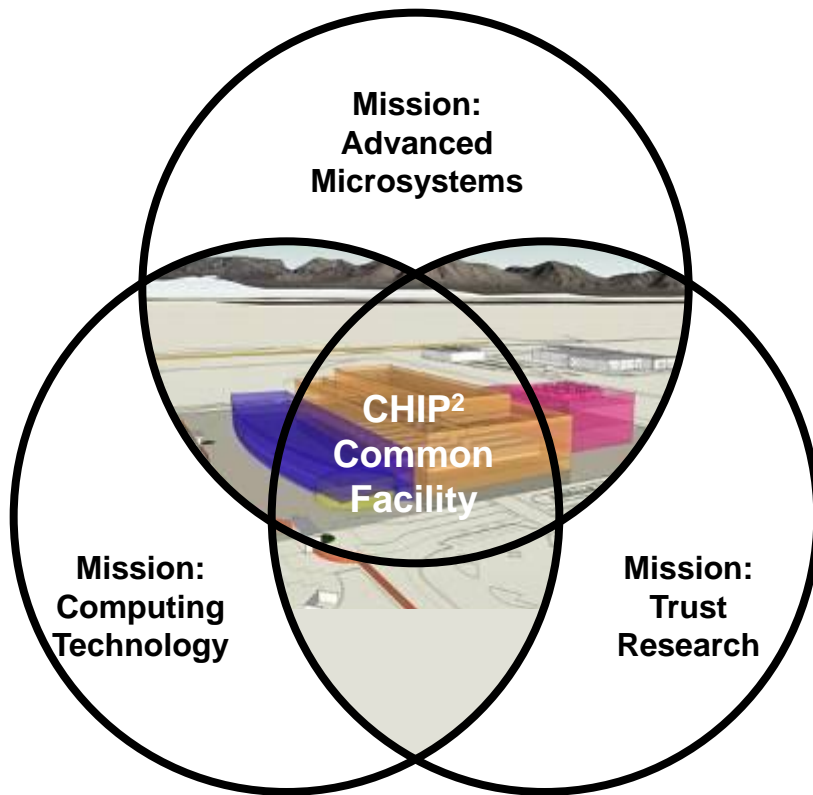


The DOE/SC nanoscience centers are different from traditional user facilities

- Defined by a scientific field, not specific instrumentation.
- NSRC staff support user projects and conduct original research.
- Capabilities involve hardware plus research expertise.



CHIP² Anticipates Future NNSA Missions



- **Advanced Microsystems**
 - Trusted strategic rad hard at 90nm
 - Circuit densities required by evolving encryption algorithms and integration
 - Integrated State of Health Sensors
 - Technologies for NNSA/DOE programs beyond NA-10 and other National Security Agencies
- **Trust Research**
 - Mitigate threats to rapidly evolving microsystems technologies
- **Computing Technology**
 - HPC beyond CMOS
 - Embedded Computing

**Mission Essential to meet the Challenges of
New Threats and a Smaller Stockpile**

■ Approach

- True heterogeneous Integration (logic, memory, silicon photonics)
 - Data Movement Oriented, not Compute Oriented!
- Not just a widget, ties in microelectronics, architecture, system software, and applications
- Question: how do we redesign the *system* given the enabling technologies to meet our mission?

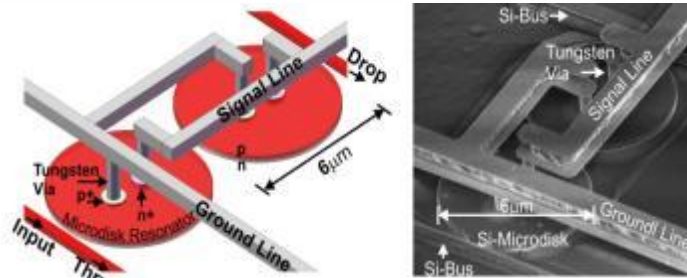
■ Significance

- Potential for 100X+ improvement in data movement capability per Joule.
- Return to balanced systems and applications
- Early exemplar of codesign for HPC



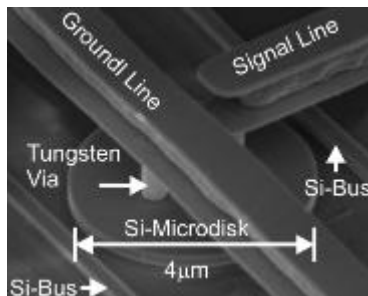
Silicon Photonics At Sandia

Free-carrier Effect (high-speed)

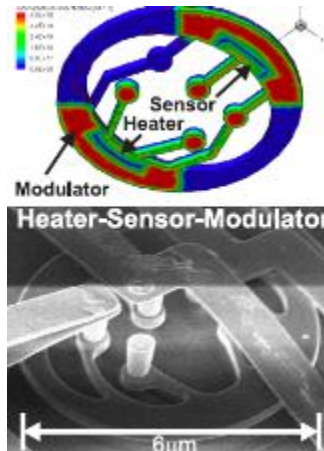


Fast Reconfigurable Interconnects

3.2fJ/bit at 12Gb/s



Resonant Optical Modulator/Filter



Thermally stabilized modulator

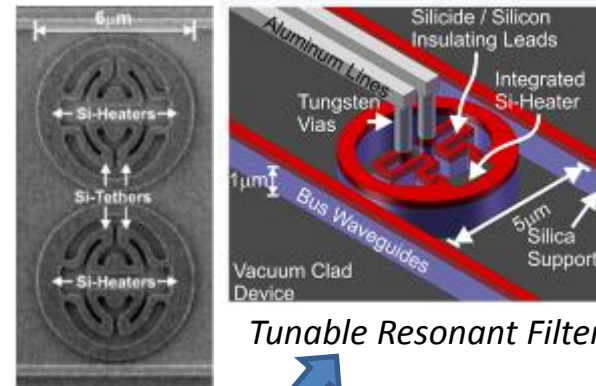
Broadband Mach-Zehnder

Filter/Switch

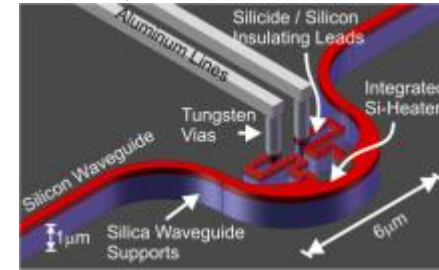
< 1V-cm at 10 Gb/s



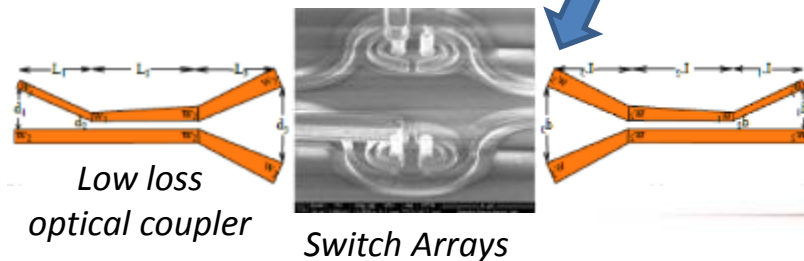
Thermal Optic Effect (wide-band)



Tunable Resonant Filter



Thermo-optic Phase Shifter



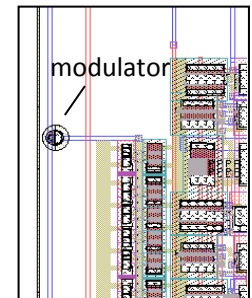
Low loss optical coupler

Switch Arrays

High-speed Ge Detector in Si



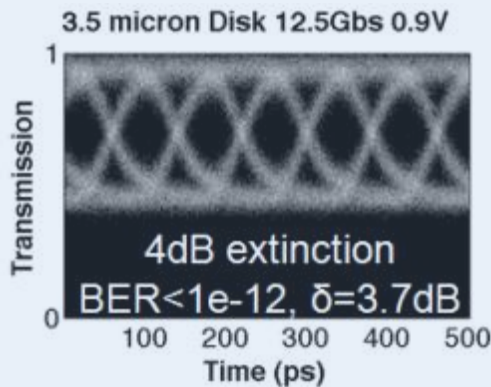
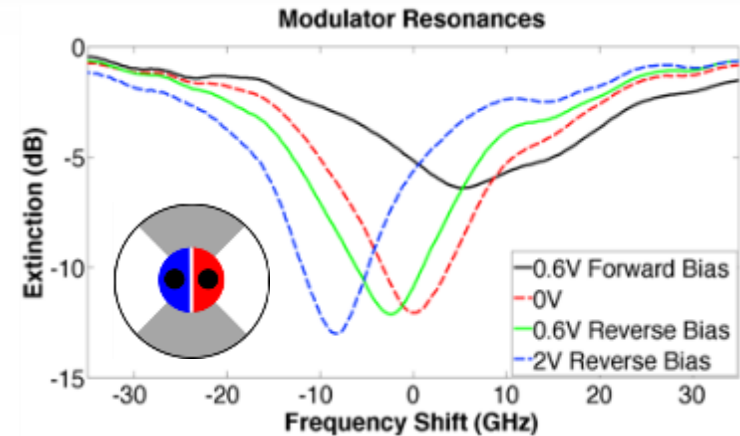
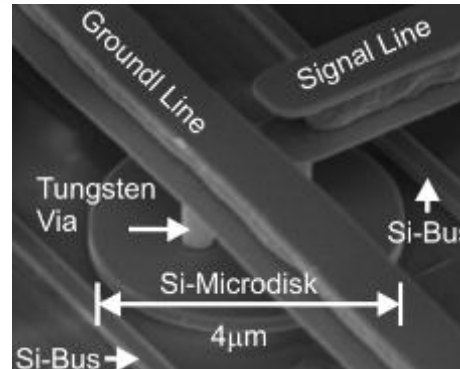
Si Photonics-CMOS Integration



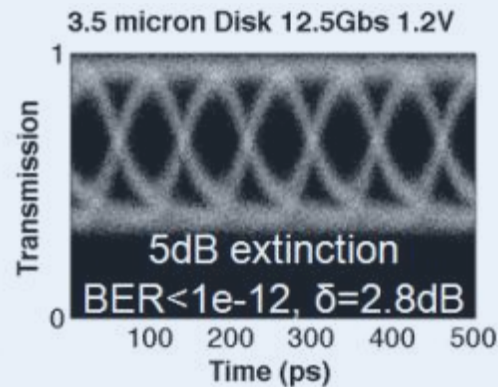
Lowest Energy Optical Modulators

Si disk resonators:

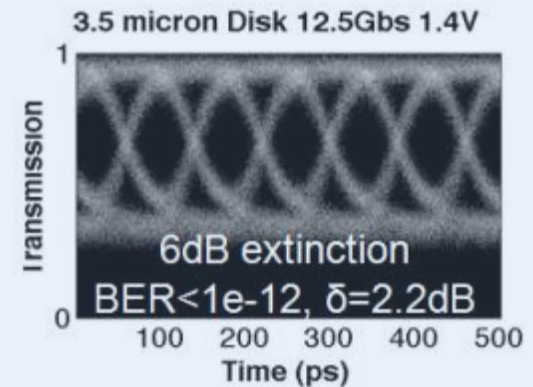
- very small device
- limit doping in ring
- differential Operation



Energy / bit: 0.9V
Analysis: 3.8fJ/bit
Measured: 3.2fJ/bit@1V



Energy / bit: 1.2V
Analysis: 6.8fJ/bit

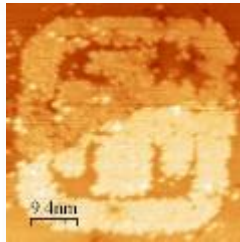


Energy / bit: 1.4V
Analysis: 10.6fJ/bit
Measured: 10.1fJ/bit@1.5V

W.A. Zortman, et. al., CLEO 2010 CThJ4

Quantum computing 101

Quantum computers promise to take computing to its ultimate quantum-coherent limit, just as lasers did for light. Multiple applications in fields like energy, medicine, and optimization are already known. The primary roadblock to development is exceptional noise sensitivity. On paper, the adiabatic quantum architecture is expected to dramatically improve robustness by maintaining a quantum computer in its lowest-energy configuration. Understanding whether this robustness is borne out in practice is an important R&D question.

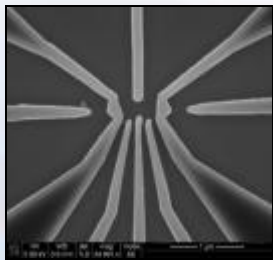


Sandia "nanologo," written to single-atom 0.7 nm precision.

Project objectives

1. Demonstrate special-purpose two-qubit adiabatic quantum optimization algorithms in
 - Neutral atoms trapped in a nanofabricated optical array.
 - Electrons trapped in silicon nanostructures.
2. Assess the potential for general-purpose fault-tolerant adiabatic quantum computing.

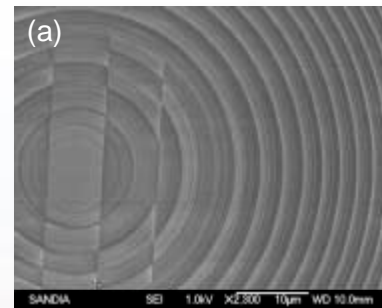
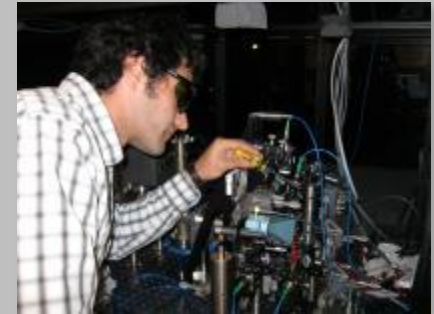
Recent accomplishments



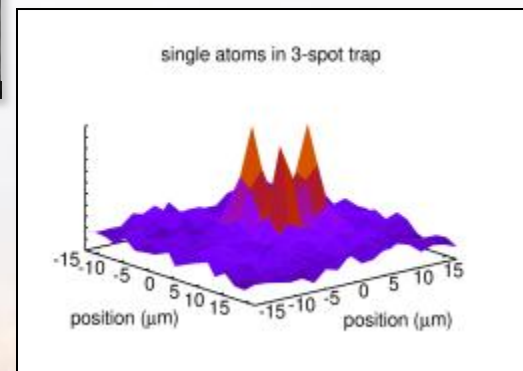
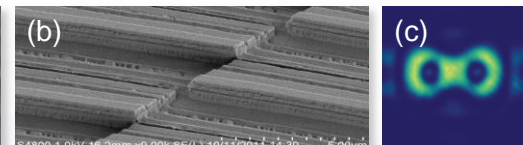
Sandia silicon nanostructure defining an "artificial atom" double-quantum-dot qubit.

- Demonstration of isolated silicon "charge" qubit
- Demonstration of atomic-scale Si lithography
- World-first fabrication of diffractive optical elements for Cs atom trapping & control
- World-first trapping of three separated Cs atoms
- Operation of Sandia's first quantum computer
 - First computation: "1 is greater than 0, ... with high probability"

Post-doc Paul Parazzoli adjusts Sandia's first quantum computer, capable of processing a single quantum bit (qubit). The computer processes information stored in an optically trapped cesium atom that is laser-cooled to 100 microkelvin in an ultra-high vacuum chamber.



(a) World-first Sandia diffractive optical element (DOE) for a two-atom trap. (b) Isometric zoom-in. (c) Image of light through the DOE.



Measured fluorescence of single Cs atoms trapped in a Sandia three-atom diffractive optical element trap.



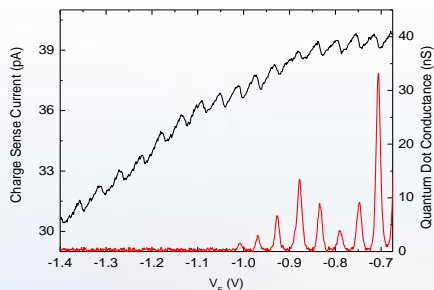
This work was supported by the Laboratory Directed Research and Development program at Sandia National Laboratories. Sandia National Laboratories is a multi-program laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.



Sandia National Laboratories

Project Accomplishments

- Developed **fabrication and measurement techniques for silicon quantum bit (qubit)** using double quantum dots
- Developed **end-to-end design** (qubits to quantum circuit) **for error corrected logical qubit** with Si double quantum dot hardware
- Developed **modeling tools to guide the fabrication, measurement, and assessment** of Si qubit and circuits.

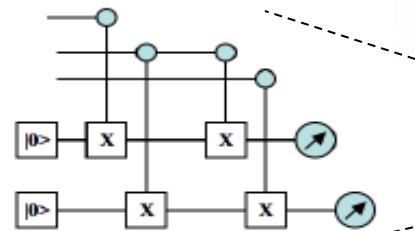


World's first single electron charge sensing in Si MOS system

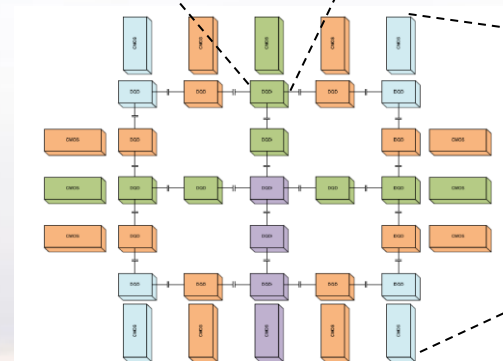
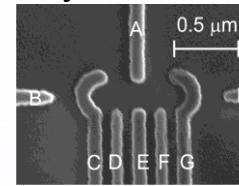
More than 24 scientific articles, 50 invited talks, and coverage in mass media

Experimental work started under QIST
GCLDRD is continuing under external funding

Quantum Circuit

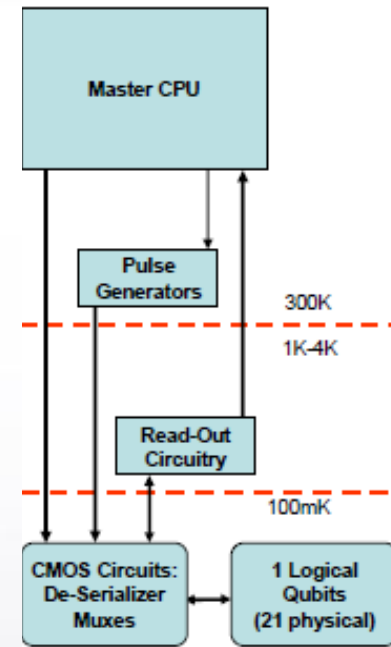


Physical Qubit



Logical Qubit

Classical Interface

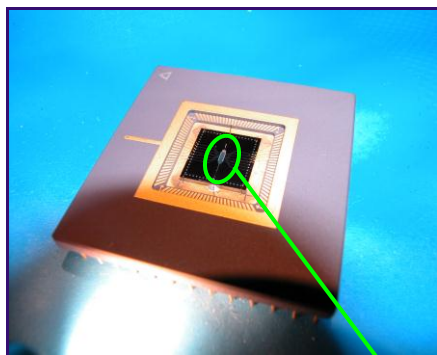


SNL MEMS 3-D Ion Trap Chip (ITC) Development for Trapped Ion Quantum Information and Mass Spectrometry Experiments

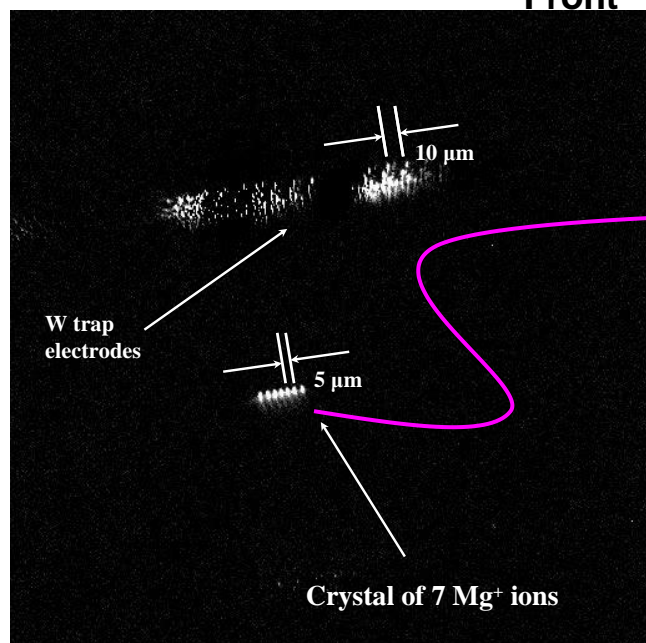
Packaged 3D ion trap chip with thru-chip and thru-package optical access



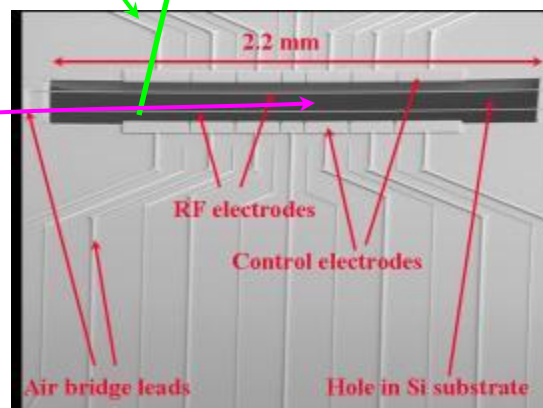
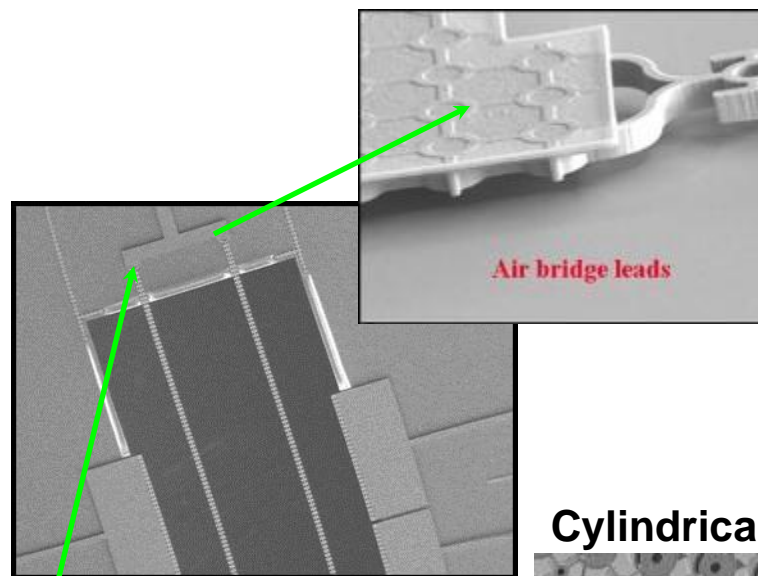
Back



Front

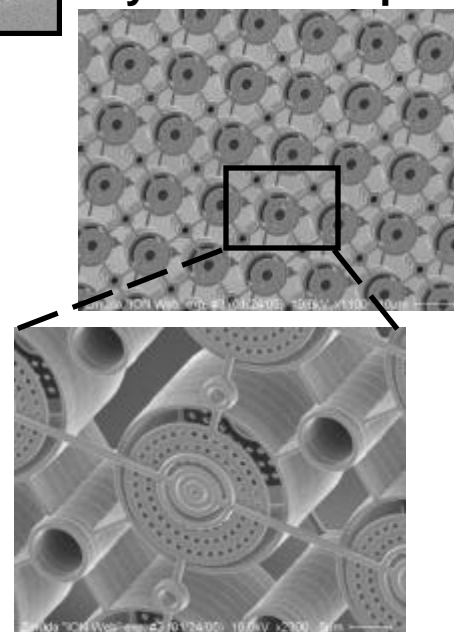


Courtesy of NIST Boulder – Wineland group



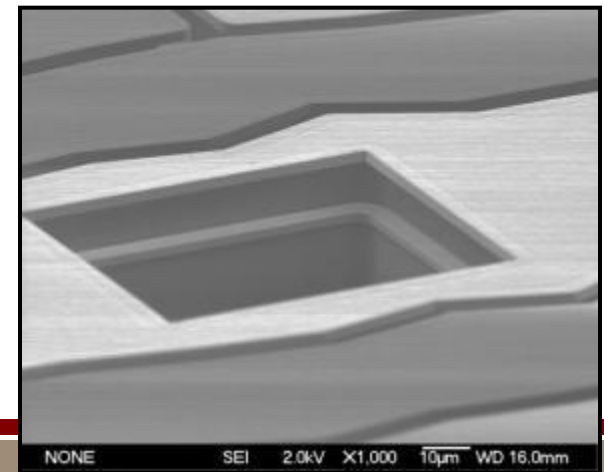
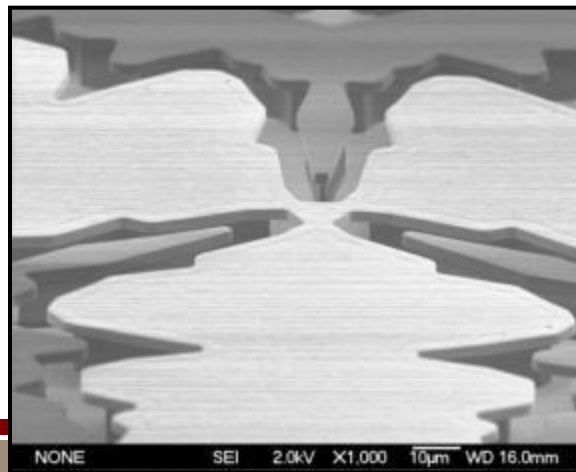
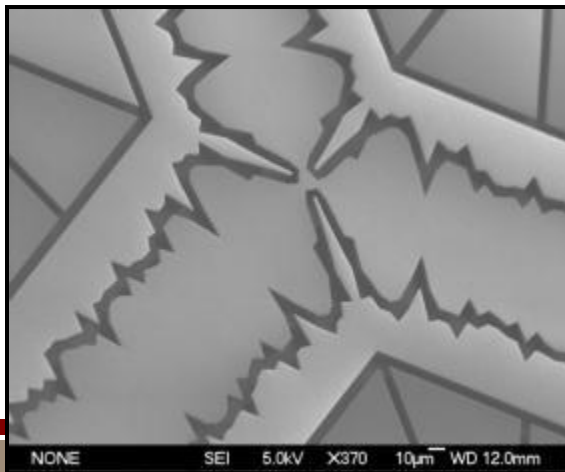
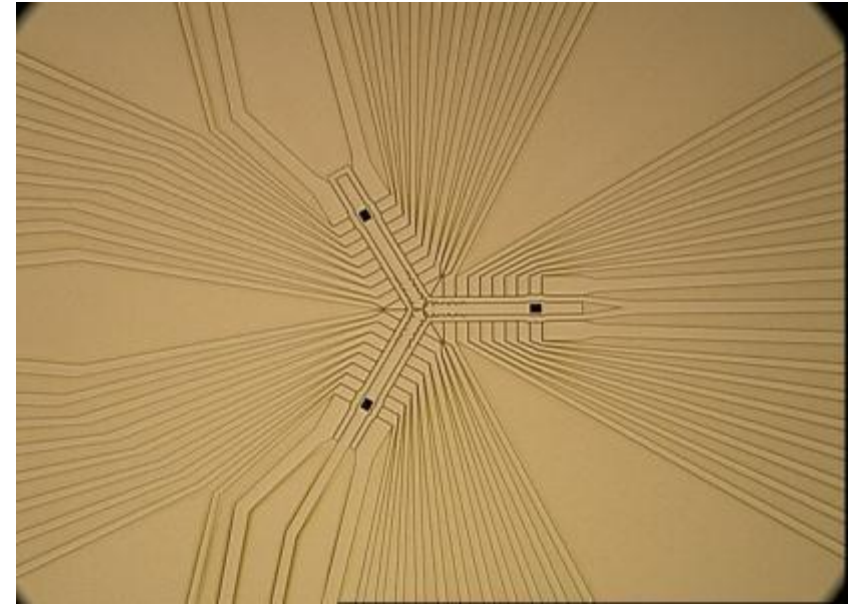
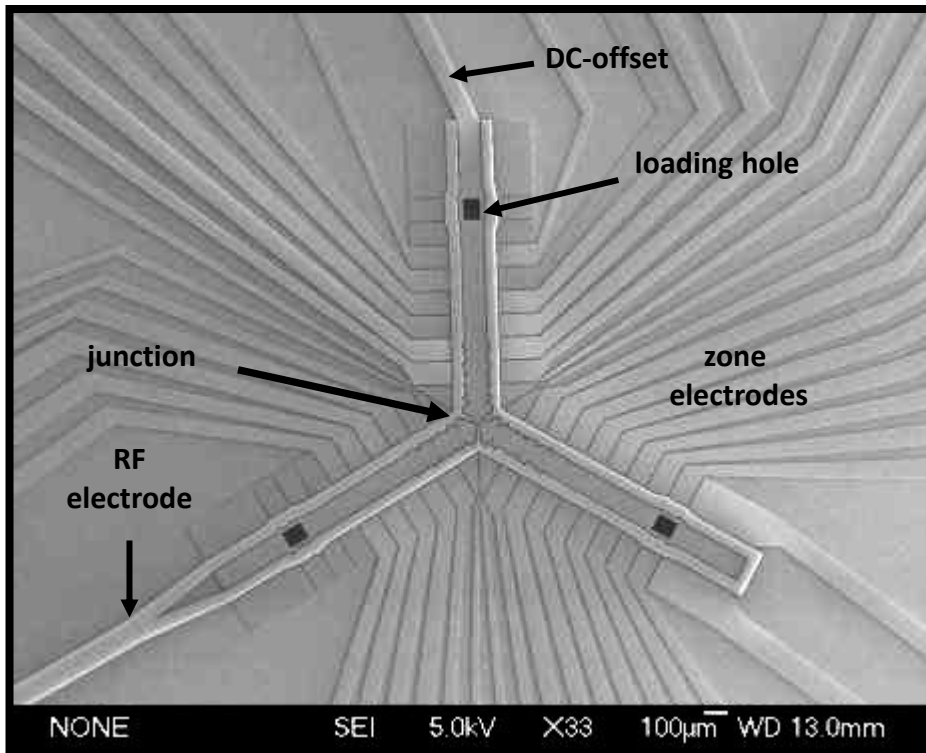
Linear Paul traps

Cylindrical traps

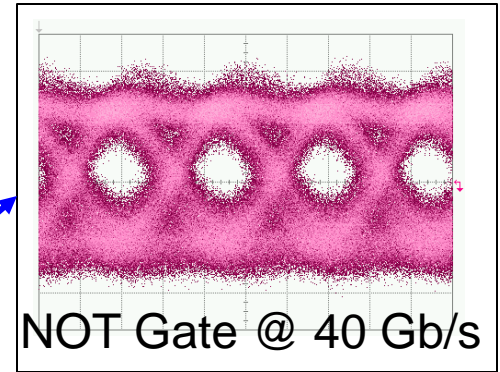
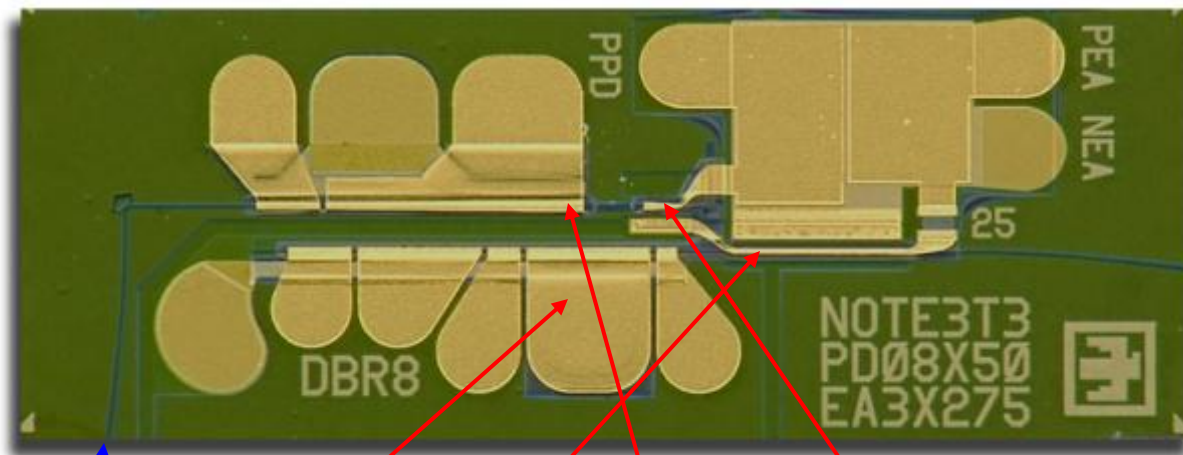


Sponsored in part by:

Y-Junction Microfabricated Ion Trap

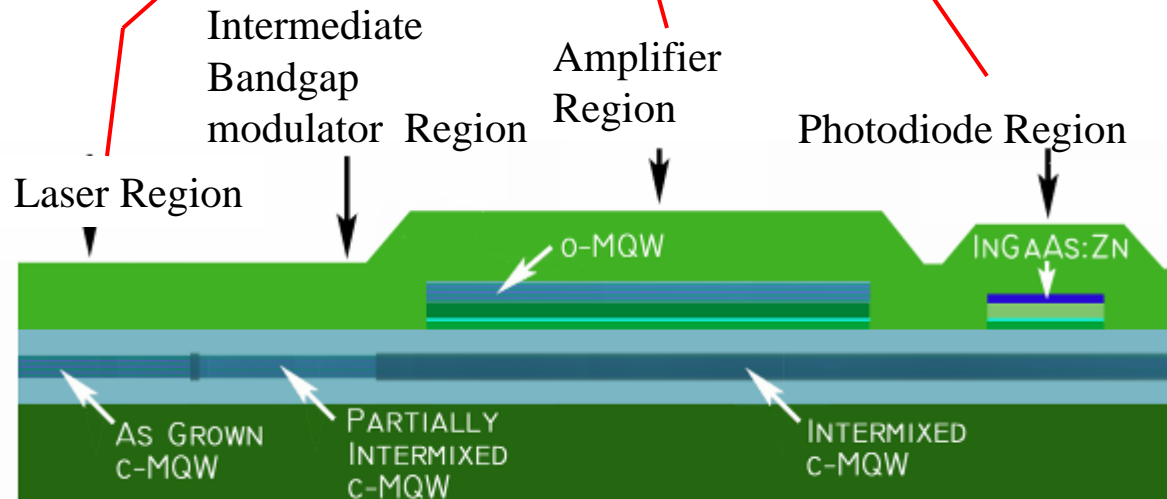


SNL Photonic Integrated Circuits (PIC)



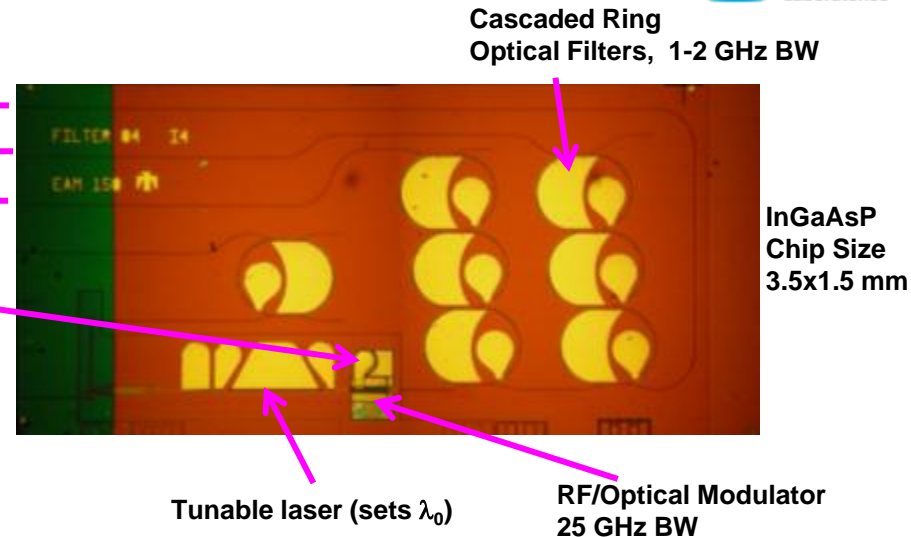
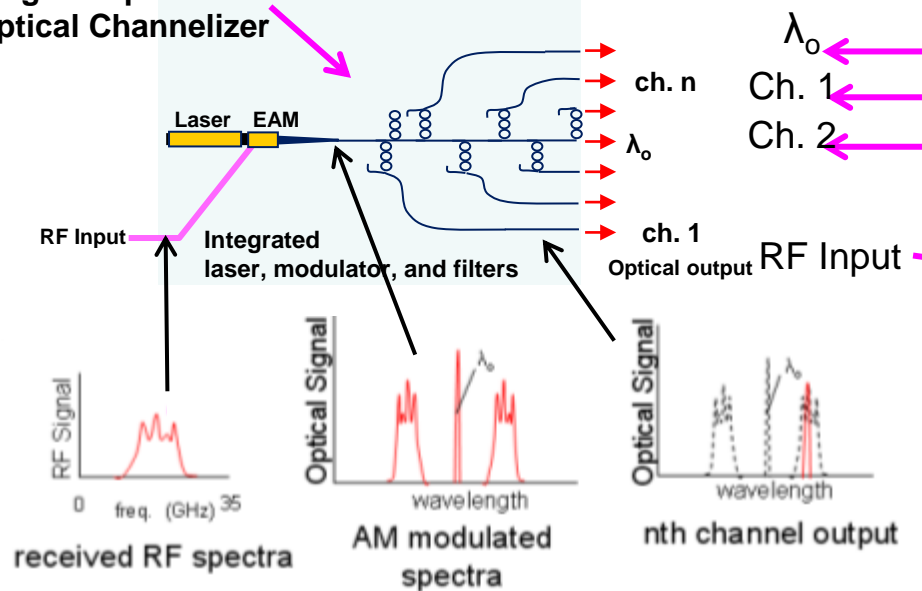
InGaAsP/InP

- 1550 nm wavelength
- State-of-the-art discrete photonic component performance from a single chip
 - Light generation, modulation, amplification, routing, switching and detection
- High-power MOPAs for intersatellite communications
- 40Gb/s optical transceivers
- WDM systems for avionics networks



SNL Optical Channelized RF Receiver PIC

Single-chip RF- Optical Channelizer



- Analyze an RF signal for frequency content
 - Filter outputs are spectral power density integrated over the filter bandwidth
- Monolithic integration with active components such as lasers and modulators enables compact, highly functional photonic integrated circuits (PICs)
- US Patent Application
 - “Photonic Circuit”, Oct. 2011
- Publications at OFC 2011
 - “Wide Dynamic Range of Ring Resonator Channel Dropping Filters with Integrated SOAs”
 - “Cascaded Double Ring Resonator Filter with Integrated SOAs”

Metamaterial Science & Technology

Year I:

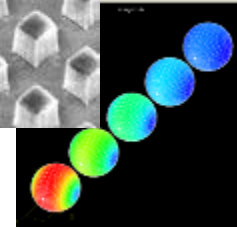
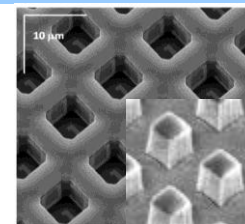
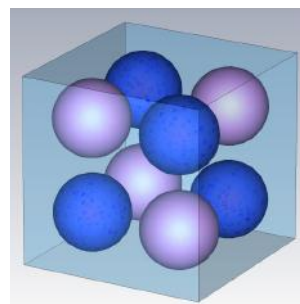
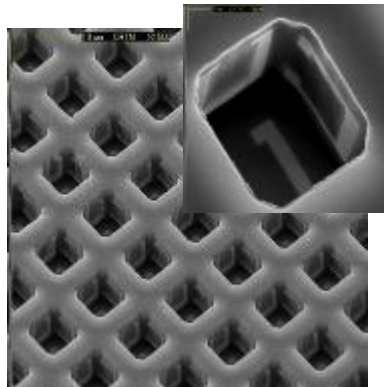
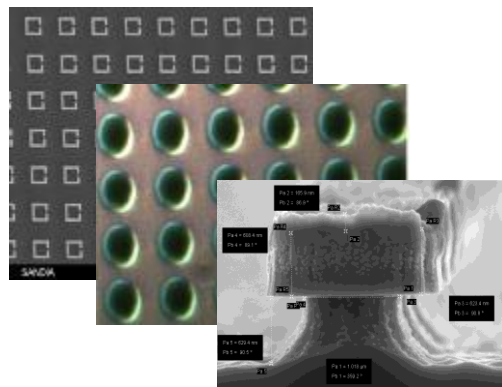
**Theory, Codes,
Materials,
IR & RF validation**

Year II:

**Demo 3D IR
metamaterials,
Downselections**

Year III:

**Full design
environment,
Low loss 3D IR MM**



• **MPL**
• **DR**
• **HPC**

Goals

2D IR & RF MMs

3D IR MM Demos

Low-loss 3D IR MM

Metrics

**RF loss ~ 1.5 dB/ λ
IR loss ~ 10 dB total 2D**

IR loss ≤ 5 dB/ λ

IR loss ≤ 0.1 dB/ λ

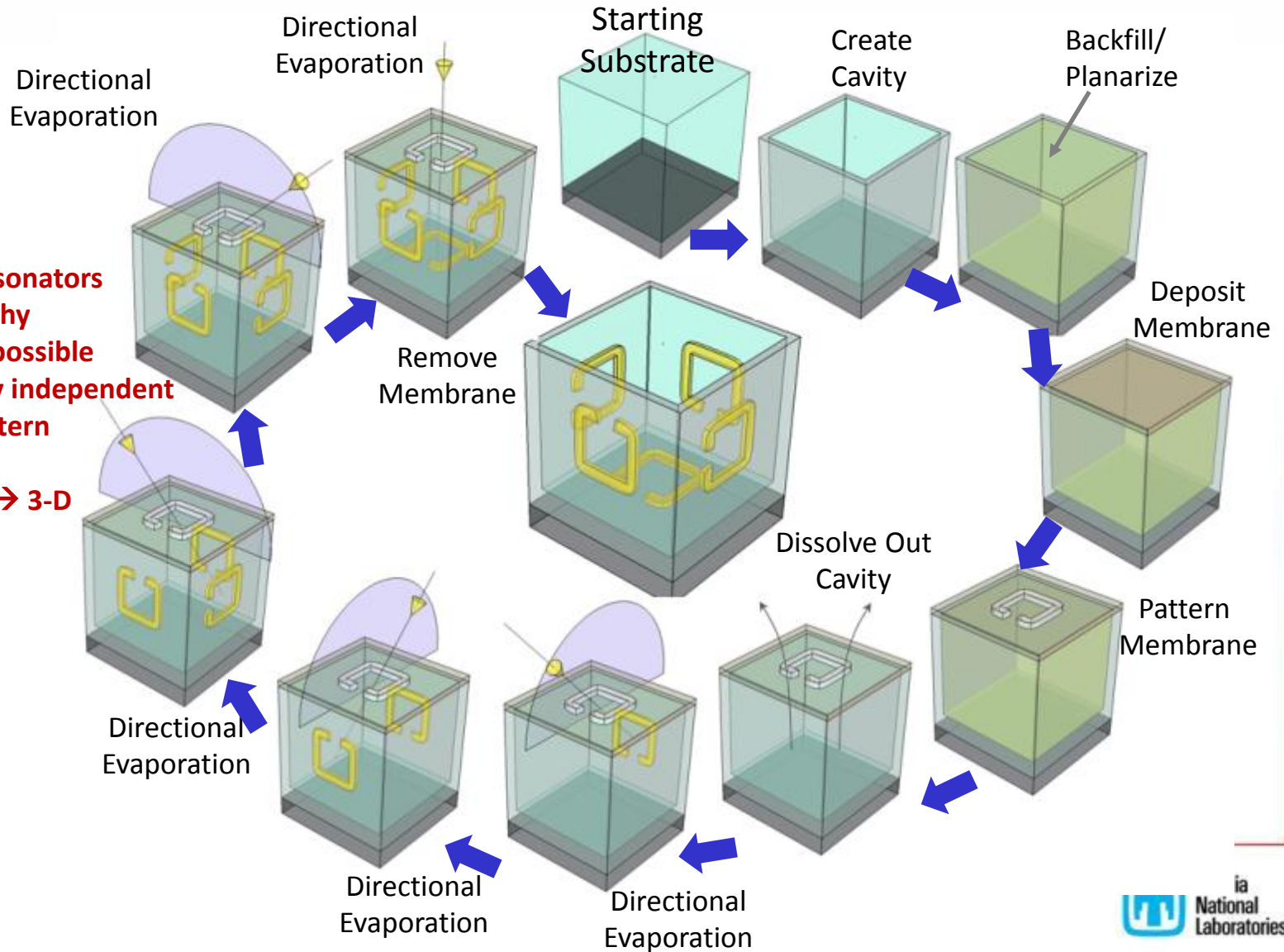
Transition

Spin-off RF & IR MM S&T programs

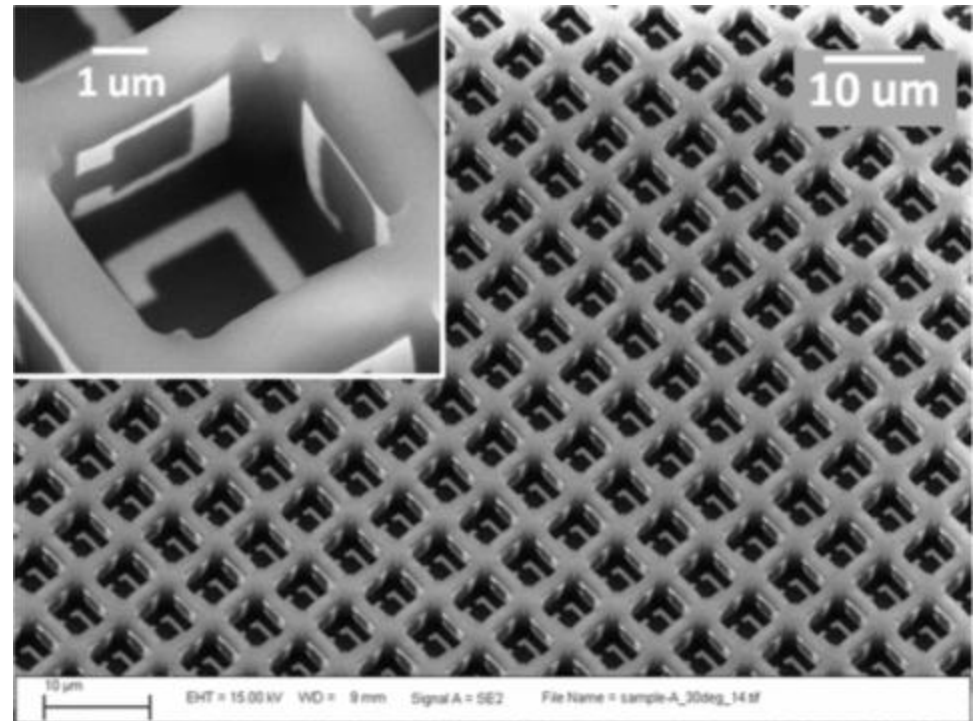
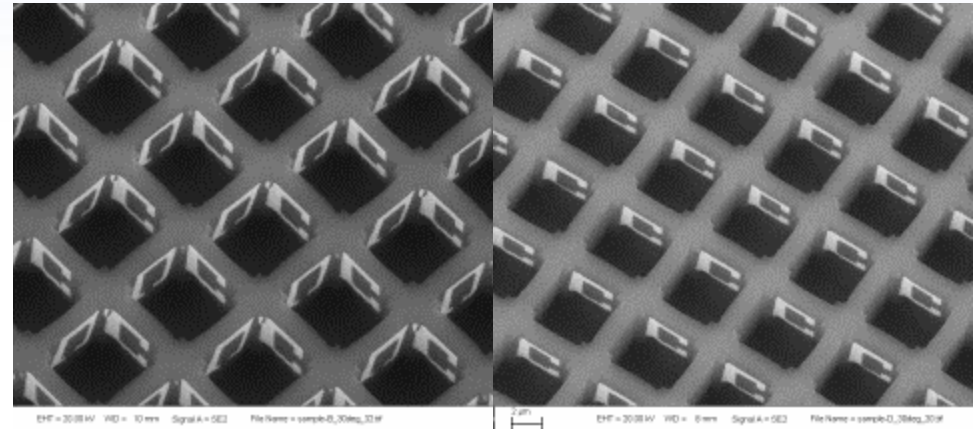
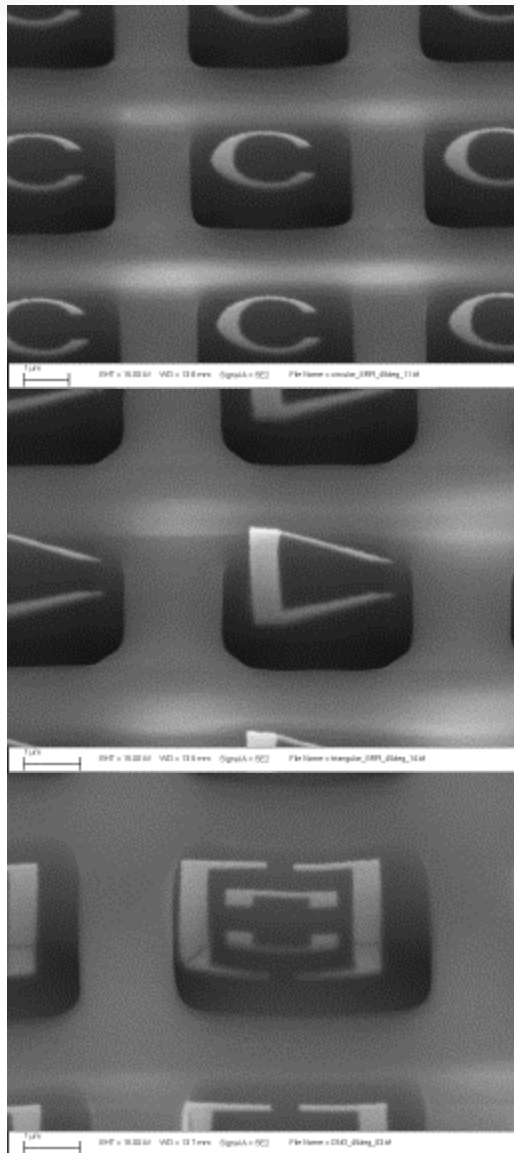
**Spin-off 3D IR
MM application**

Membrane Projection Lithography: MPL

- Out-of-plane resonators
- Planar lithography
- Many patterns possible
- Cavity geometry independent of resonator pattern
- Scalable
- Layer-by-layer → 3-D

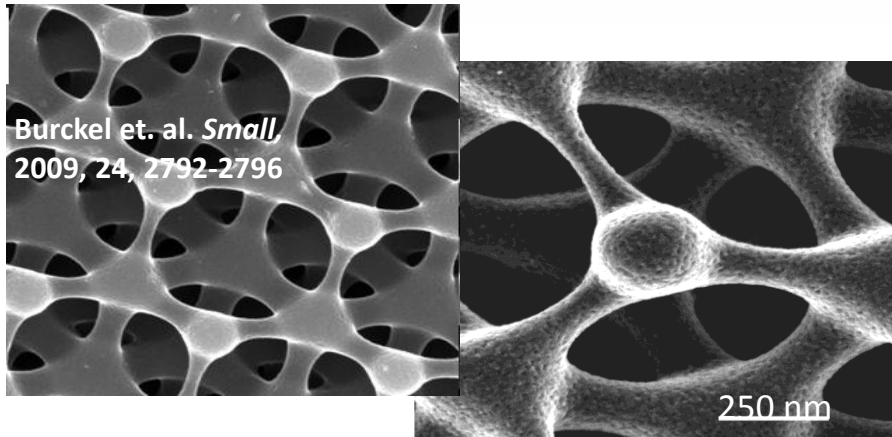


Deposition through Membrane Demonstrated



Use of Lithography to Make 3D structures

1. Lithographically defined porous carbon electrodes



Energy Applications

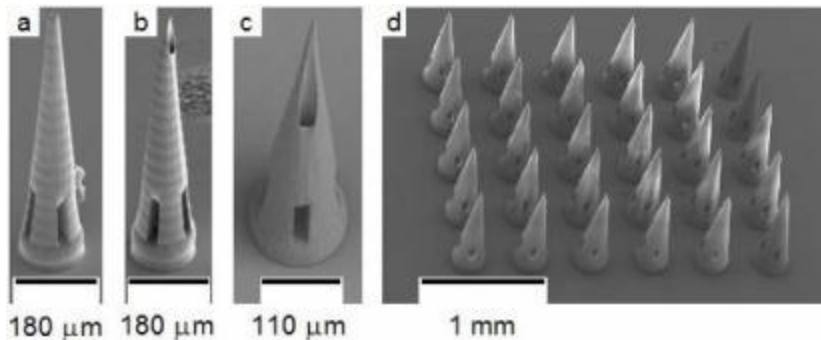
- fuel cells
- ultracapacitors
- batteries

Sensors

- non enzymatic glucose detectors
- ion selective electrodes

3D Graphene Structures

2. Microneedles for sensing and/or drug delivery



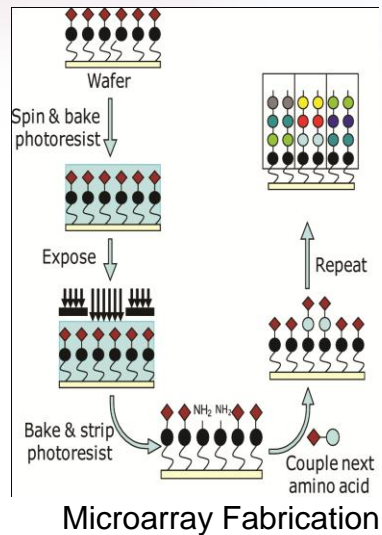
Transdermal In Vivo Sensors

Hollow bore microneedles can be integrated with electrode transducers to determine the immediate physiological state of an individual for medical applications and defense of the warfighter

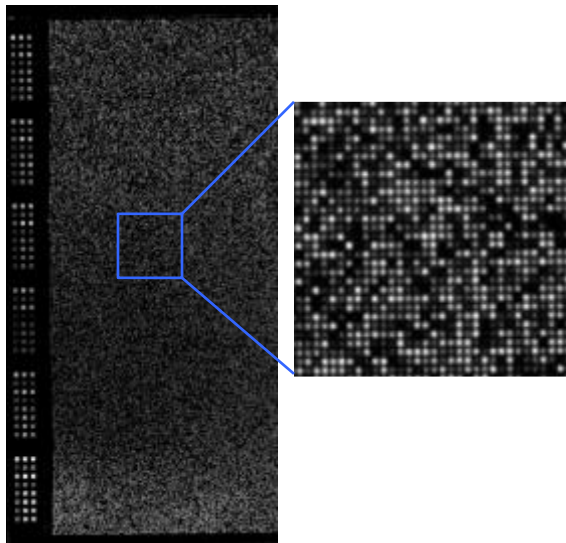
DOI: 10.1111/j.1744-7402.2007.02115.x

Roger Narayan (UNC/NCSU)

Objectives and Program Relevance

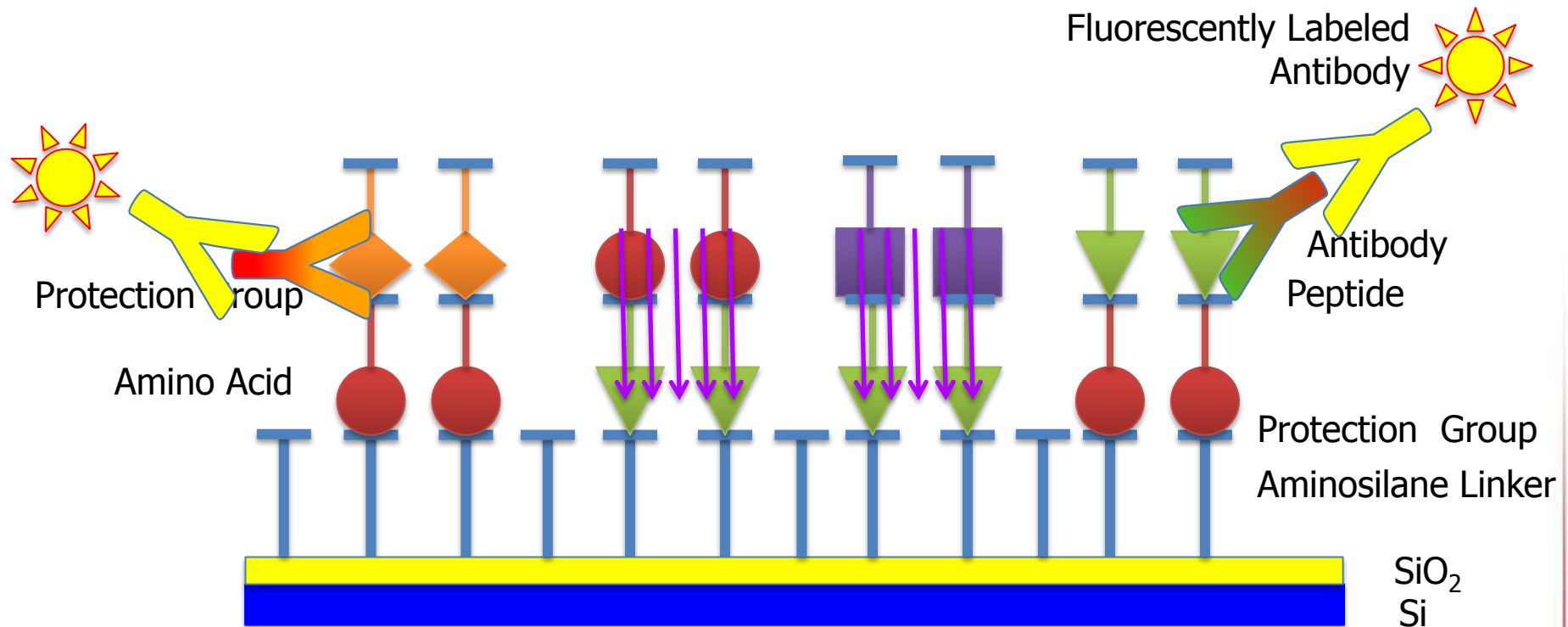


- Project Goal – develop a rapid medical diagnostic tool to identify exposure to biological warfare agents
- Approach – detect immune response to the biological agent, not the agent itself; take advantage of amplification within human immune system
- Technology – a microarray of thousands of different peptides to identify antibodies present in patient's blood; a single array will detect multiple agents; initially developed by ASU
- Sandia's Role – establish optimized, manufacturable microfabrication process to meet DHS application needs; provide microarrays for LLNL use
- Sponsors – DHS S&T Directorate, DoD Defense Threat Reduction Agency; supports programmatic goals of IHNS SMU
- Sandia's participation requested by DHS S&T Undersecretary because of Sandia's microfabrication and bioscience expertise



Prototype ASU Microarray

Site-Specific Peptide Assembly

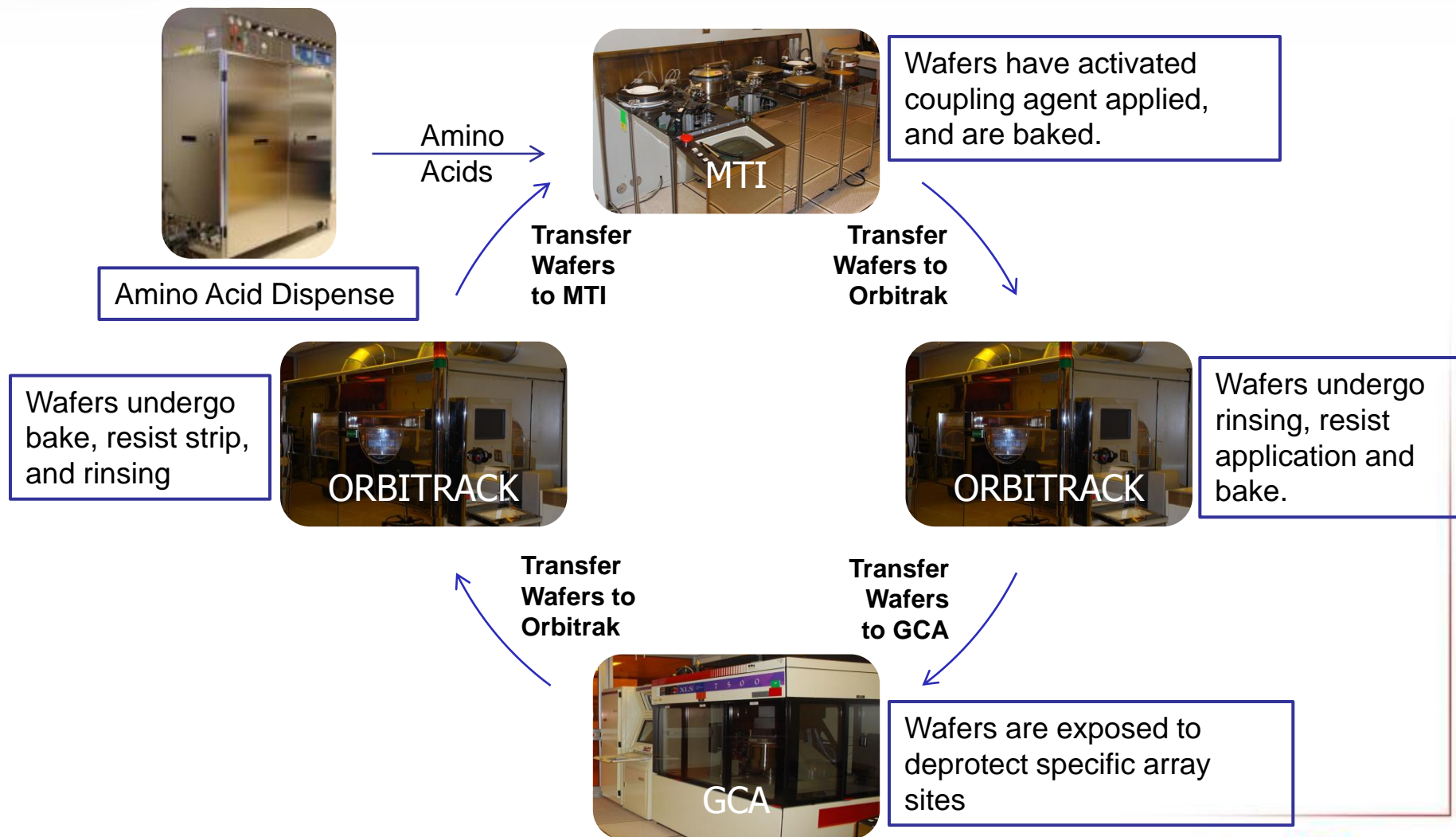


- Exposing photoresist at array site generates acid, removing acid-catalyzed protection group to permit amino acid binding via peptide linkage.
- Repeat to produce monomers using 20 amino acids across 10^5 array sites
- Repeat to produce dimers using 20 amino acids across 10^5 array sites
- Repeat to produce 20-mer peptides



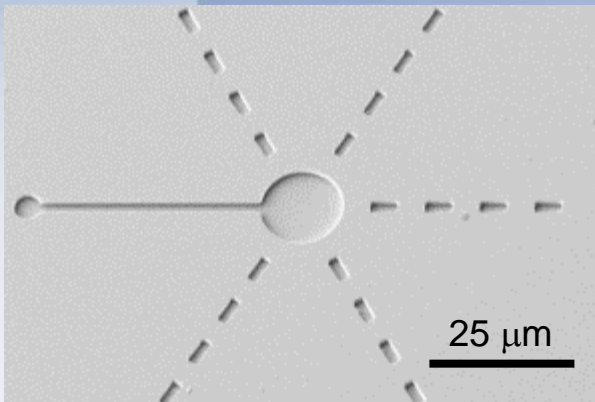
Manufacturing Development

SiFab processing bay dedicated to microarray manufacturing development

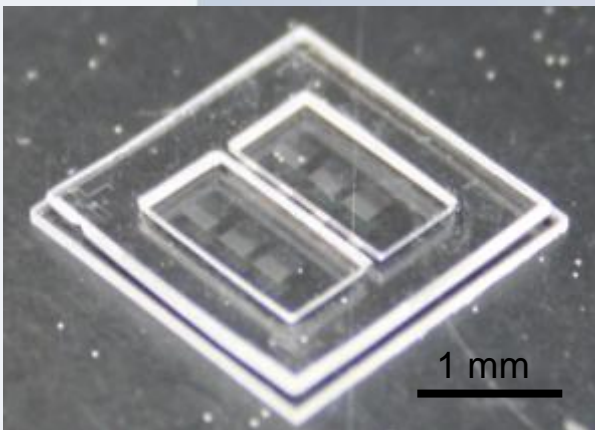
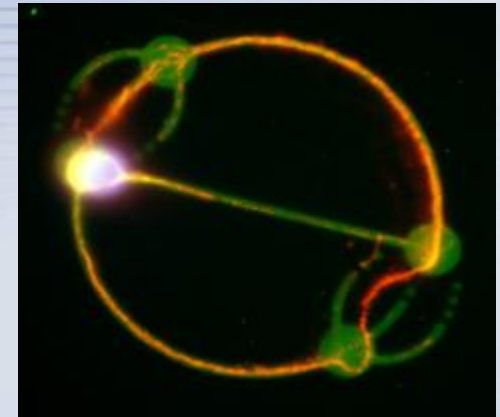
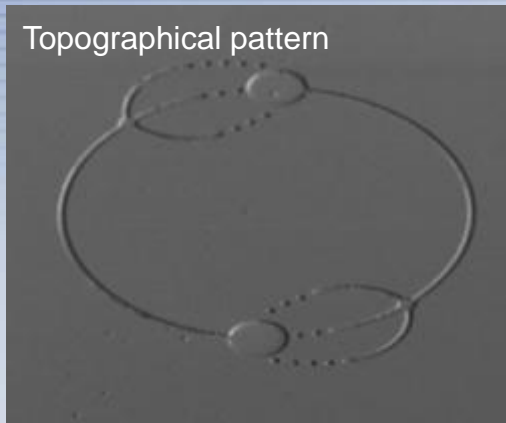


Engineered Neural Circuits

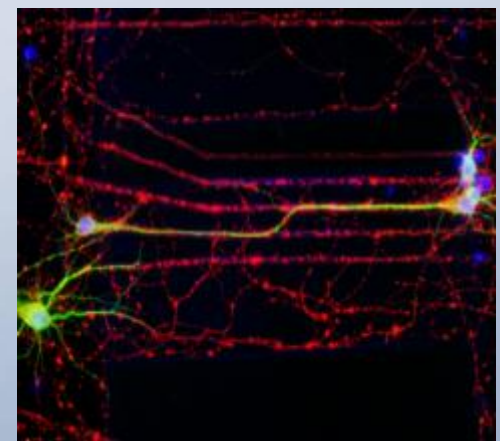
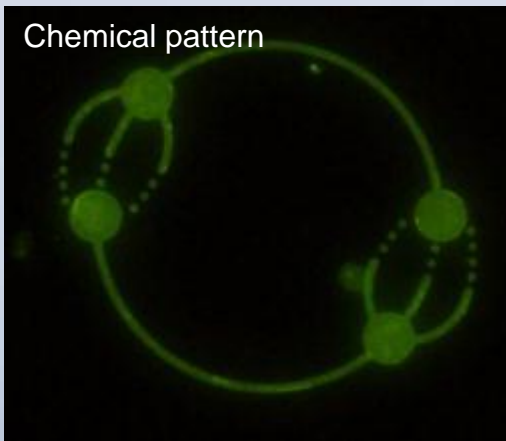
- Provides a sensitive platform to test the efficacy of vaccines and countermeasures against chemical and biological agents
- Model biological system to study circuitry for advanced computing architectures



Topographical pattern



Chemical pattern



End of Moore's Law?

- We are at least as close to the end of the roadmap as we are the 90nm node
- The only parameter that is staying on the Moore's Law exponential is fab cost
- We are still using the same basic lithography as we were at the start of the roadmap
- It is time for a new architecture, and neuro-inspired computing is very promising
 - We cannot be limited by our present conception of computing
 - We cannot be bound to mimicking the brain
 - We must exploit the parameters (physics/chemistry/biology/math) of candidate technologies on their terms

It takes time to learn the best uses for new technologies

Development of the coke furnace enabled iron cheap enough for large structures.



Image source: http://www.igreens.org.uk/canoeing_stuff.htm

The first iron bridge located on River Severn in England was built near the first coke furnace in Coalbrookdale in 1779. It used the best known wooden carpentry techniques and thus was severely over-engineered.



Image source: http://en.wikipedia.org/wiki/File:Coalport_br1.jpg

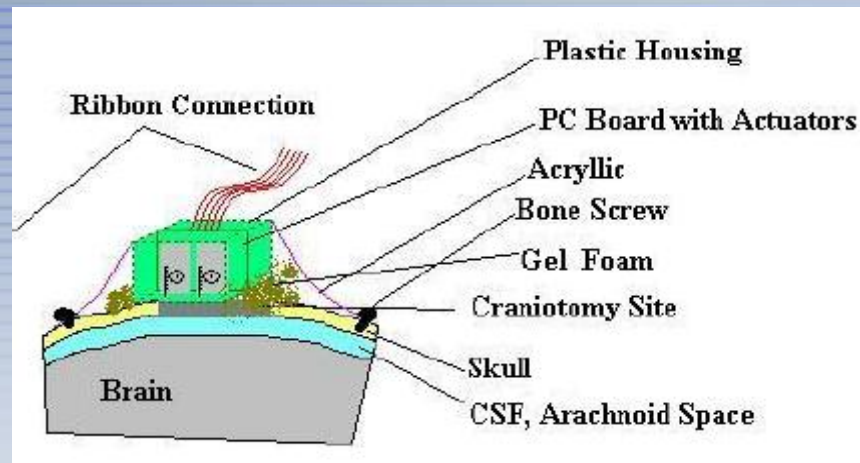
When an additional bridge was needed in 1818 at Coalport over the same river, it used design insights based on properties of cast iron and *required only half the cast iron as the first iron bridge!*



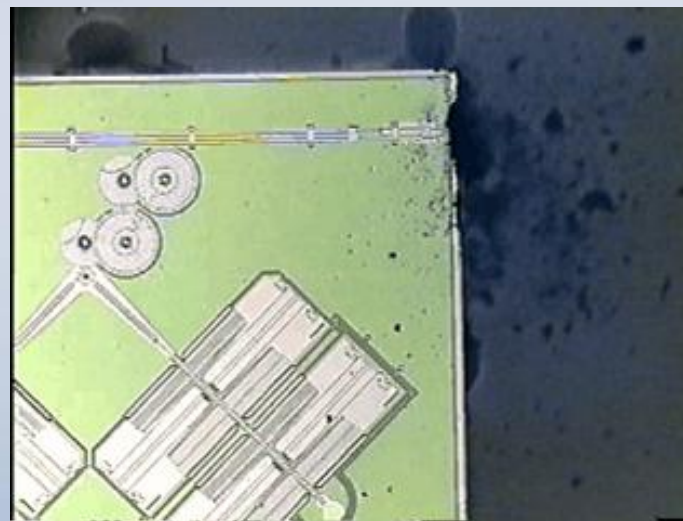
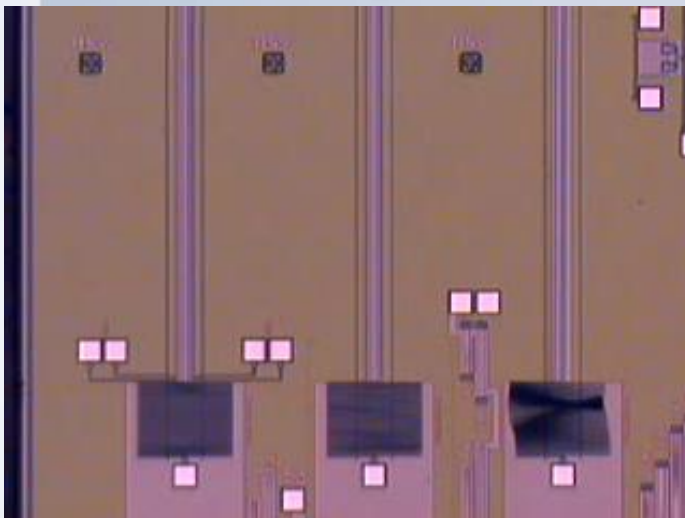
Sandia National Laboratories

Micromachined Neural Probes

- First off-chip coupling to the external world (4mm extension)
- Testing under way at Arizona State University
- New designs have higher force, longer throw and better functionality with ratcheting thermal actuators



Current design
using thermal
actuation



First probe
design using
electrostatic
actuation

Summary

- Sandia has incredible people and facilities that can make just about anything one could imagine
- Sandia has experience transition science to application
- Multidisciplinary, Multi-Institutional teams do great things, especially when unbound by convention
- Emerging technologies are best developed with new concepts that exploit the natural advantages of the technologies